APPLYING A COMPENSATED PULSED ALTERNATOR TO A FLASHLAMP LOAD FOR NOVA*

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ABSTRACT

The Compensated Pulsed Alternator (CPA) is a large rotating machine that will convert mechanical, rotationally stored energy into a single electrical impulse of very high power. It is being optimized for driving flashlamps in the very large Nova Nd:glass laser system. The machine is a rotary flux compression device, and for maximum performance, it requires start-up current. We report upon a circuit that will provide this current and that will also assist in triggering the flashlamps. This circuit has been tested with a 200 kJ capacitor bank and it is now being tested with a small 200 kJ CPA. Large Nova-size machines will require output energies in excess of 5 MJ. We also present empirically tested formulae that will assist in matching the Nova flashlamp load to any given size CPA machine.

Introduction

The Compensated Pulsed Alternator (Compulsator) is a very large rotary energy store that is a candidate source for driving the 5 to 10 thousand flashlamps that will pump the Nova laser. It is presently under development by the University of Texas at Austin (UT) and the Lawrence Livermore Laboratory (LLL). In the final (Nova) version, the machine will deliver a pulsed output energy of 5 to 20 MJ in about a half millisecond time with a peak voltage of about 13 kV. The order of a 100 MJ total energy will be needed for the Nova flashlamps.

At present, a small 200 kJ Compulsator is starting through a comprehensive test program at UT. The magnetics, mechanics and electrical characteristics of the machine are to be determined, and the machine will be used for driving 16 parallel flashlamps in an LLL laser amplifier head. The test data for the small machine will be used in the design of the large Nova-size machines.

In this paper, we report upon the circuit that will couple the 200 kJ Compulsator to its 16-flashlamp load. A similar circuit will be used for each Nova Compulsator, where hundreds of lamps will be driven by a single machine. These circuits provide start-up current for the Compulsator as well as providing triggering to all of the parallel flashlamp circuits.

Matching the Compulsator to the flashlamp load is another important task in this program. Empirical data have been collected for the large Nova flashlamps that enable us to characterize this type of load over a broad range of operating conditions. Briefly, we find that the energy W delivered to a flashlamp is given by, $W = fK\, i_p^{3/2} \Delta t$ (Eq. 1), where i_p is the peak current through the lamp and Δt is the time for full-width at half-maximum (FWHM) of the current pulse. The factor f is a unitless current waveshape form factor that has a range of values from 0.8 to 1.02. For the Compulsator waveshape, f is very nearly unity (± 2%). The parameter K has been found to be constant within two percent over a broad range of energies and pulse durations. It is defined by $K = V/\sqrt{i}$, where V is the voltage across the flashlamp and i is the current through it. Thus the flashlamp resistance is

$$R = V/i = K/\sqrt{i}. \qquad (2)$$

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14. ABSTRACT

The Compensated Pulsed Alternator (CPA) is a large rotating machine that will convert mechanical, rotationally stored energy into a single electrical impulse of very high power. It is being optimized for driving flashlamps in the very large Nova Nd:glass laser system. The machine is a rotary flux compression device, and for maximum performance, it requires start-up current. This circuit has been tested with a 200 kJ capacitor bank and it is now being tested with a small 200 k.J CPA. Large Nova-size machines will require output energies in excess of 5 MJ. We also present empirically tested formulae that will assist in matching the Nova flashlamp load to any given size CPA machine.

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Derivations of these formulae and examples of their use are presented in the paper.

Test Circuit

The simplified circuit for testing the 200 kJ Compulsator and load is given in Fig. 1. The start-up capacitor will store 2.5 to 10 kJ of energy. It will be initially charged to a negative voltage to facilitate immediate current flow when the ignitron switch is fired. At the same time, the flashlamp reflector is bumped by the pulse transformer, breaking down the flashlamps. A small reverse current flows through the lamps into the start-up capacitor, helping them to turn on.

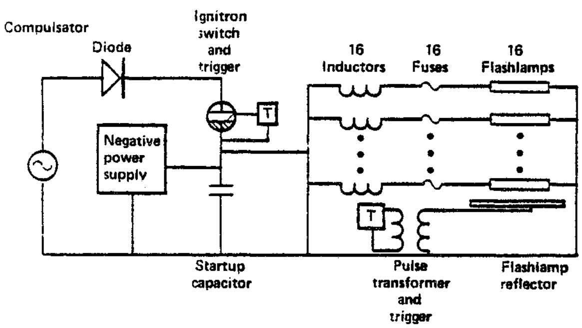


Fig. 1: Simplified Compulsator test circuit.

As current flows through the Compulsator, it becomes compressed and amplified. This causes the start-up capacitor to be positively charged. Current then flows through the lamps in the positive direction, and they are driven in the normal manner by the machine's impulse.

After the positive current impulse, the machine provides a soft zero crossing, and the ignitron switch and flashlamps go out. This extinction is facilitated by the diode, because it allows a small reverse voltage to appear across the switch that helps to clean up hot ions. The second positive pulse will appear about 3 ms after the switch extinguishes. This should be ample time for the ignitron to recover, but if it does not, a backup vacuum interrupter is being provided (not shown in Fig. 1) that will insure that repeated pulses do not occur.

Summary of Testing to Date

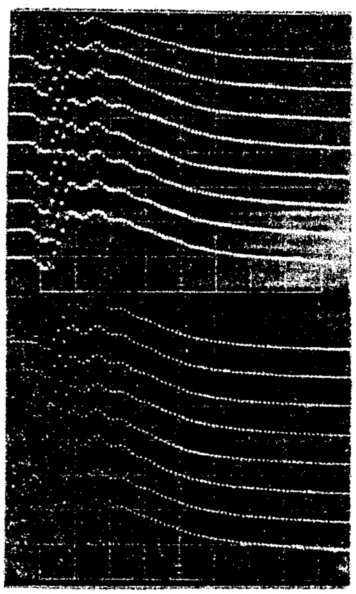
The Compulsator load circuit was tested at LLL with a 0.01-F capacitor bank in place of the Compulsator, and a start-up capacitor comprised of one 175 μF can. Initial testing of the flashlamp circuit demonstrated that the flashlamps hold off 12 kV before they self-fire. Testing of the flashlamp/start-up-capacitor circuit alone demonstrated that all 16 lamps would fire when the flashlamp reflector circuit was bumped and the start-up capacitor was charged to minus 4 kV. Verification of flashlamp firing was provided by 16 current bugs that drive two 8-channel scopes.

The system was next tested without diodes, but with the 0.01-F capacitor bank (200 kJ at 6.3 kV) substituted for the Compulsator in Fig. 1. The flashlamp reflector was pulsed 150 μsec before the ignitron was fied to assure that all flashlamps would be conducting before the low impedance 0.01-F capacitor bank shunted the start-up capacitor. (With the Compulsator, this time delay will probably not be necessary). The circuit performed normally, and the flashlamp current was first negative because of the negative voltage from the start-up capacitor. This negative current reversed direction as the positively-charged bank capacitor rung into the start-up capacitor and discharged through the flashlamps, Fig. 2.

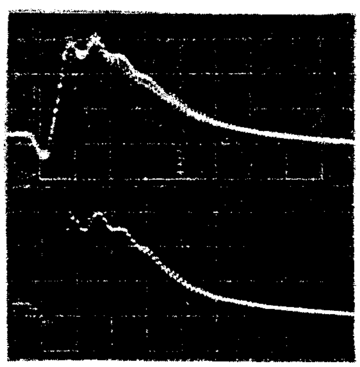
These tests demonstrate that the circuit provides the triggering to the flashlamps as anticipated, and that all 16 parallel flashlamp circuits balance well by virtue of a 125 μH series inductor in each circuit leg. The circuit and flashlamps are presently being shipped to Austin, Texas where testing of the 200 kJ Compulsator will begin shortly.

Characterizing the Flashlamp

In 1965, Goncz[1] characterized a flashlamp by the equation $\rho^2 j = k_1$ = constant, where ρ is the plasma resistivity and j is the flashlamp current density. Goncz was dealing with small tubes with bores completely filled with plasma. This relationship



(a)



(b)
200 μsec/div.

Fig. 2: Current waveforms from sixteen parallel flashlamps. Sixteen parallel flashlamps are driven first negatively with a 175-μF, -5 kV start-up capacitor, followed 150 μsec later with a 0.01-F, +6.4 kV capacitor bank. a). Sixteen circuits displayed individually from a single shot. b). Eight circuits per trace, showing that parallel flashlamp circuits balance well on each shot.

leads directly to Eq. (2), i.e. $R = K/\sqrt{i}$, where the "flashlamp constant", $K = \frac{\ell}{d}\,\frac{k_1}{\pi}$ (Eq.4). Later, in 1974, Dishington, et al.[2] introduced an empirical relationship for the effective plasma diameter d in Eq. (4) to account for the early growth of the plasma streamer before the bore is filled: i.e. (in mks units), $d \cong 9.5 \times 10^{-4}(W/\ell)^{0.6}$ (Eq. 5) where W/ℓ is the deposited energy per unit length in the gas. They also noted the existence of a transition region between d = d(free space) and d = d(bore), where the final arc growth slows down due to the influence of the flashlamp wall. Finally, Noble and Kretschmer[3] and others have noted a fill pressure and gas type relationship for the flashlamp constant. For xenon, this relationship is $K_1 = 1.27(P/450)^{0.2}(\ell/d)$, (Eq. 6), where P is the fill pressure in Torr.

The present Nova standard flashlamp has an arc length ℓ = 1.12-m, a bore diameter d = 0.015-m, and a fill pressure of 300 Torr xenon. By use of Eq. (6), we have $K = 1.27(300/450)^{0.2}(1.12/0.015) = 87.3$, assuming the bore to be completely plasma filled (neglecting Eq. (5)).

Note that since $R = K/\sqrt{i}$, we have $R_{min} = K/\sqrt{i_p}$ at peak current and $V_p = i_p R_{min} = K\sqrt{i_p}$. We can therefore define K as, $K = V_p/\sqrt{i_p}$ (Eq. 7). Using this definition, K was calculated for the Nova lamps by measuring the peak voltages and currents, recorded simultaneously from many discharges. The range of energies varied from 5 to 27 kJ, the peak currents varied from 2.8 to 6 kA and the current FWHM times varied from 480 to 800 μsec. Over this range, K remained constant at 86.5 ± 2. This value agrees with the K = 87.3 number obtained from the Noble/Kretschmer relationship. Because of the long pulse duration of 0.5 msec or more desired for Nova, we are assuming (for now) that the bore becomes filled early and that Eq. (2) is valid with K = 87 ohms$\sqrt{\text{amp}}$.

Using Eq. (2) for the resistance, the instantaneous power dissipated by the flashlamp will be $i^2R = Ki^{3/2}$ The energy dissipated by the flashlamp will therefore be,

$$W = K \int_{t_1}^{t_2} i^{3/2}\,dt \qquad (8)$$

The value under this integral will depend upon the waveshape of the current pulse. For a square pulse (constant current), $t_2 - t_1 = \Delta t$ (i.e., the total pulsewidth and the FWHM are the same), and

$W_{sq.} = Ki_p^{3/2}\Delta t$ (Eq. 9). Combining (8) and (9), we can define a waveshape form factor as,

$$f \equiv \frac{W}{W_{sq.}} = \frac{\int_{t_1}^{t_2} i^{3/2} dt}{i_p^{3/2}\Delta t} = \int_{x_1}^{x_2} y^{3/2} dx \qquad (10)$$

where the normalizations of $x = t/\Delta t$ and $y = i/i_p$ are made. Form factors for a number of waveshapes have been calculated,[4] and they vary from a minimum of 0.8 (for a triangular wave) to slightly more than 1. For the anticipated Compulsator waveform, f is very nearly unity (± 2%). Rearranging (10) and substituting (9) we obtain Eq. (1), namely,

$$W = fW_{sq.} = fKi_p^{3/2}\Delta t \qquad (1)$$

and this is the equation that enables us to match the flashlamp load to the Compulsator. For the Nova flashlamp, with the Compulsator waveform,

$$W \cong 87\ i_p^{3/2}\Delta t. \qquad (11)$$

Matching Flashlamps and Compulsators

Equation (11) applies for a single Nova-size flashlamp. As a rule, two of these lamps will be driven in series, and many in parallel by a single Compulsator. For a flashlamp system of n_s series by n_p parallel lamps, the required Compulsator energy (assuming f = 1), $W_c = n_s n_p W = Kn_s n_p i_p^{3/2}\Delta t$ (Eq. 12), and the required Compulsator peak current, $i_c = n_p i_p$ (Eq. 13). The peak Compulsator voltage will be, $V_c = n_s V = n_s K\sqrt{i_p}$ (Eq. 14), and so the peak Compulsator power is $P_c = V_c i_c = Kn_s n_p i_p^{3/2} = W_c/\Delta t$ (Eq. 15). Two examples are given in Table 1, assuming K = 87. With the small prototype Compulsator, we desire to provide 200 kJ into 16 parallel Nova flashlamps with a half-millisecond pulse. A typical 5 MJ Nova Compulsator would provide a half-millisecond pulse into 200 parallel by 2 series flashlamps (400 total). The actual terminal output voltage of the machine will need to be somewhat higher than that given in the table to make up for losses in the system. Note that losses will also increase the peak power and the energy output requirement, but these should be small (∿ 10%) in a typical system.

	200 kJ Prototype	5 MJ Nova
Flashlamps		
n_s	1	2
n_p	16	200
Total lamps	16	400
W (kJ)	12.5	12.5
i_p (kA)	4.4	4.4
Δt (msec)	0.5	0.5
Compulsator		
W_c (kJ)	200	5000
i_p (kA)	70	870
Δt (msec)	0.5	0.5
V_c (kV)	5.7	11.5
P_c (GW)	0.4	10

Table 1

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